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Climate Change and the Future Fire Environment in Ontario:

Fire Occurrence and Fire Management Impacts

Ontario

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Climate Change and the Future Fire Environment in Ontario:

Fire Occurrence and Fire Management Impacts

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Abstract

Fire weather and fuel moisture scenarios from General Circulation Model (GCM) climate projections were used with forest fire occurrence models and a level of protection analysis system (LEOPARDS) to estimate the impacts of climate change on the fire management system in Ontario. GCM climate scenarios show that the mean summertime temperature in Ontario will increase by 1 to 1.5°C by 2040 and by about 4 to 5°C by 2090. This change in temperature will be accompanied by relatively small changes in regional precipitation. These changes in temperature and precipitation will lead to a drier forest floor, resulting in an estimated 24% increase in the number of lightning fires by 2040 and an 80% increase by 2090. This estimated increase in the number of lightning fires is conservative because it does not include any changes in lightning activity over current levels. Expected increases in lightning strike activity will add to the increased occurrence of lightning-caused fires. The numbers of people-caused fires occurring in Ontario are expected to increase by at least 7% in 2040 and 26% in 2090, however these are also considered conservative estimates because changing patterns in frequency and amount of rainfall, changing demographic patterns, and landscape change were not addressed in this study. Overall, the total number of fires occurring in Ontario's fire management area is expected to increase 15% by 2040 and 50% by the end of the century. These increases in fire activity and the heightened fire behaviour potential caused by drier fuels lead to an estimated 30% increase in the number of fires that escape initial attack by the year 2040 and an 80% increase by 2100 given current resource levels. The increased fire load is expected to increase the cost of fire management in the province 16% by the year 2040 and 54% by the year 2090 over year 2000 costs, exclusive of inflation or other factors.

Résumé

La formulation de scénarios concernant les conditions météorologiques propices aux incendies et la teneur en humidité des combustibles forestiers à partir des projections climatiques d'un modèle de circulation générale (GCM) a été utilisée conjointement avec des modèles d'incidence des feux de forêt et un système d'analyse du niveau de protection (LEOPARDS) pour évaluer les répercussions des changements climatiques sur la gestion des feux de forêt en Ontario. Les scénarios de changement climatique du modèle GCM montrent que la température moyenne estivale en Ontario augmentera de 1 °C à 1,5 °C d'ici 2040 et d'environ 4 °C à 5 °C d'ici 2090. Ces changements de température seront accompagnés par des changements relativement peu prononcés des taux de précipitation en région. Ces variations de température et des taux de précipitation contribueront à rendre le couvert forestier plus sec, avec pour conséquence une augmentation du nombre des incendies de forêt causés par la foudre estimée à 24 % d'ici 2040 et à 80 % d'ici 2090. Ces augmentations estimative du nombre d'incendies causés par la foudre sont conservatrices car elles ne prennent pas en compte les changements de l'activité orageuse par rapport aux niveaux actuels. Les augmentations attendues du phénomène de foudroiement viendront s'ajouter à l'augmentation de l'incidence des incendies de forêts causés par la foudre. En Ontario, on s'attend à ce que le nombre des incendies de forêt imputables à des facteurs humains augmente d'au moins 7 % d'ici 2040 et de 26 % d'ici 2090, bien que ces estimations soient encore une fois conservatrices puisque certains facteurs comme l'augmentation de la fréquence et du volume des précipitations, les changements démographiques et la transformation du paysage n'ont pas été retenus dans cette étude. Dans l'ensemble, on s'attend à ce que le nombre total des feux de forêt à l'intérieur de la zone de gestion des incendies de l'Ontario augmente de 15 % d'ici 2040 et de 50 % d'ici la fin du siècle. Ces augmentations du nombre de feux de forêt et le comportement potentiellement plus intense des incendies causés par les combustibles secs entraînent, à leur tour, une augmentation du nombre de feux ayant résisté à une lutte initiale estimée à 30 % d'ici 2040 et à 80 % d'ici 2100 - étant donné le niveau actuel des ressources. En Ontario, on s'attend également à ce que l'augmentation de la charge combustible contribue à hausser les coûts de la lutte contre les incendies de 16 % d'ici 2040 et de 54 % d'ici 2090 par rapport aux dépenses enregistrées au cours de l'année 2000 et cela, sans tenir compter de l'inflation ou d'autres facteurs.

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Introduction

Fires have occurred in the boreal forest of Canada for thousands of years. Today fires occur both naturally from lightning and through human activity in the forest. Forest fire management agencies reduce potential wildfire damage to human values in the forest by suppressing fire in important areas. The daily planning and resource positioning procedures of a forest fire management agency rely on estimates of the distribution and abundance of fires on any given day, on potential fire behaviour, and on suppression resource availability. As such, for a comprehensive examination of the potential impacts of climate change on the managed forest, the impacts of a changing climate on each of these elements must be understood.

Studies of the potential impacts of climate change on fire danger levels in Canadian forests (Flannigan and Van Wagner 1991, Flannigan *et al.* 1998, 2000, Stocks *et al.* 1998, Wotton *et al.* 1998) have typically used General Circulation Model (GCM) outputs to project fire danger using components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). Study results indicate that the future fire climate (as measured by fire danger indices) will become more severe across much of Ontario. Increases in summertime temperatures of 3 to 5 °C across the province (Colombo *et al.* 1998) and regional changes in precipitation (both to higher and lower amounts) increase the seasonal severity rating (a component of the FWI System used as a summary of summertime fire weather severity). In addition to increases in seasonal fire severity indices, a number of these studies also predict increases in the frequency of occurrence of extreme fire danger in some areas of the country (e.g., Stocks *et al.* 1998).

Although most of the previous work on climate change and fire impacts addresses changing levels of fire danger, it has not focused on the explicit development of future fire occurrence or burned area scenarios. Price and Rind (1992,1993), however, did develop a lightning occurrence model within the Goddard Institute for Space Studies (GISS) GCM and used that model to predict increases in lightning-caused fire occurrence of 30 to 77 % across the U.S. for a doubled CO_2 scenario (Price and Rind 1994). Recently, Wotton *et al.* (2003) examined potential changes in the numbers of people-caused fires expected across Ontario using daily weather information from the future climates generated by two GCMs. They found that decreased fuel moisture levels in future climate scenarios led to an increase in people-caused fire occurrence of around 50% by 2100. Neither of these studies examined the impact of increased fire activity on fire management agency operations.

In general, forest fires can be classed as either lightning- or people-caused. The ignition, smouldering, and detection of lightning-caused fires, while dependant on cloud-to-ground lightning strikes, also depends on the moisture content within the organic layer of the forest floor. A lightning strike ignition can smoulder for several days or even weeks before being detected. People-caused fires result from a variety of human activities on the landscape including recreation (e.g., camping, hiking, or hunting) or industrial activities (e.g., timber production or railway transportation).

This study uses lightning- and people-caused fire occurrence models developed specifically for Ontario with GCM projections of future climate and Ontario's level of protection analysis software, LEOPARDS (see McAlpine and Hirsch 1999) to estimate the impacts of climate change on the fire management organization both in terms of numbers of escaped fires and with respect to changes in operational costs.

Methods

General Circulation Model Fire Weather Scenarios

General Circulation Model Scenarios

A series of climate scenarios for future decades were created by applying monthly temperature and rainfall anomalies to current daily fire weather station records following the methods used by Stocks *et al.* (1998). Monthly anomalies were obtained from the Canadian Climate Centre's first generation coupled ocean atmosphere model (CGCM1) (Flato *et al.* 2000). The Canadian Climate Centre model is made up of an atmospheric model with 10 vertical levels and a horizontal resolution of approximately 3.75° in both latitude and longitude. The atmospheric model is coupled daily to an ocean model with 1.8° resolution in both latitude and longitude. The simulation starts nominally in 1850 and ends in 2100. This GCM includes forcing from both effective CO_2 and aerosols following the prescribed forcing scenarios described by Mitchell *et al.* (1995). Effective CO_2 concentrations up to 1990 are used from observed atmospheric values, after which they are assumed to increase at a rate of 1% per year. Aerosol loadings were assumed to be zero at the "spin up" time (1850), followed the observed increase to 1986, and followed a linear trend (described in Boer *et al.* 2000) after 1986 to 2100.

Temperature and precipitation anomalies were calculated using the GCM years centred around 2000 (1995-2004) as a baseline, which corresponded generally to the 1992-2001 period in the weather station archive maintained by the Ontario Ministry of Natural Resources (OMNR). The mean monthly temperature from the baseline period was subtracted from the corresponding monthly temperature from each future decade to create a temperature difference. A decade of future climate was defined as the 10 years surrounding the base year of each decade (i.e., the future climate for the decade 2040 comes from the years 2035-2044). Mean monthly precipitation from the future decade was divided by the mean monthly precipitation from the corresponding baseline decade to create a change ratio. The Canadian Climate Centre created three separate runs of the GCM from 1900-2100 using the same greenhouse gas and aerosol forcing scenarios. Monthly mean temperature and precipitation values for each decade were created by averaging results from these three runs. As such, each monthly mean temperature anomaly and precipitation ratio from each decade is the average of 30 observations (3 scenarios with 10 years each).

Each GCM grid cell covers approximately 400 km × 300 km. To associate a temperature and precipitation anomaly with each of the OMNR weather stations, which are irregularly spaced, the OMNR's cubic-spline interpolation routine (Flannigan and Wotton 1989) was used to interpolate anomalies to each weather station site. The sites of the GCM grid cell centres and OMNR weather stations used are shown in Figure 1.

Fire Weather and Fire Danger

To create the fire climate of a future decade, the monthly anomalies were applied to the daily data from the OMNR fire weather station archive from the years 1992-2001 (corresponding to the period over which lightning records were available). The monthly temperature anomaly was added to each daily temperature value, and the daily precipitation values were multiplied by the change ratio to estimate future precipitation. This method does not account for changing storm frequency in the future, but merely provides an average adjustment to the recorded amount of rain.

Once the monthly temperature and precipitation anomalies were applied to the OMNR weather dataset, these future daily fire weather scenarios were inserted into the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) to generate future fire danger scenarios. The indices created from the FWI System were used in fire occurrence prediction models described later in this report.

Future scenarios of lightning strike occurrence in Ontario were unavailable for this study. However, by using the monthly anomaly approach of Stocks *et al.* (1998), the future fire weather patterns developed were based on

Figure 1.
General Circulation Model grid point locations (✚ signs) and OMNR weather station locations (• circles) used in LEOPARDS analyses.

current weather patterns. Only the daily temperature and the strength of any particular rainfall were affected. The frequency and timing of rainfall events were not changed in the future decadal scenarios from those observed in the 1992-2001 period. For example, if it rained on May 5th of year 0 (1992) in the observed record, then it rained on May 5th of year 0 in each future climate as well. Only the magnitude of that rainfall changed in the model. The observed lightning record from 1992-2001 was used for each future decadal scenario. As the weather patterns in the future scenarios were the same as the observed period, lightning occurrence in the future scenarios matched storms and associated rainfall.

Forest type in each of the ecoregions across Ontario (and hence percentage of closed canopy forest as a predictor in the lightning ignition models) is assumed not to have changed in the future scenarios. An ecoregion is a large ecosystem characterized by unique ecological factors (including climate, physiography, vegetation, soil fauna and land use) (Ecological Stratification Working Group 1996).While it is not the purpose of this paper to address changing vegetation patterns in response to climate change, this assumption has significant implications given that changing forest type may affect the probability of ignition in future fire climates.

Lightning-caused Fire Occurrence Scenarios

The occurrence of a detected lightning fire on the landscape can be divided into several phases: ignition from a lightning strike, smouldering, emergence as a spreading surface fire, and detection (Kourtz and Todd 1992, Anderson *et al.* 2000, Anderson 2002). Data on lightning fire (or potential lightning fire) behaviour between the stages of the lightning strike and a detected fire is heavily censored. In Ontario, individual lightning strikes are detected by the provincial lightning detection system, providing an estimate of the total number of potential ignitions on the landscape is available. For each ecoregion in Ontario (Figure 2), models have been developed that estimate probability of a lightning strike causing a sustainable ignition in the forest floor. These models were developed using generalized linear modelling techniques with summaries of daily lightning strikes, fire weather, and fuel moisture into a grid of 20 × 20 km cells across the province. In addition, models to predict the day, following ignition, that a smouldering ignition will begin spreading actively enough to be detected were also developed using historical fire occurrence, daily fuel moisture, and potential fire behaviour information. The development of these models and their functional forms are described in Wotton and Martell (2005). For this study, we used lightning strike data from 1992 to 2001, excluding 1999 due to problems with data archival during that fire season.

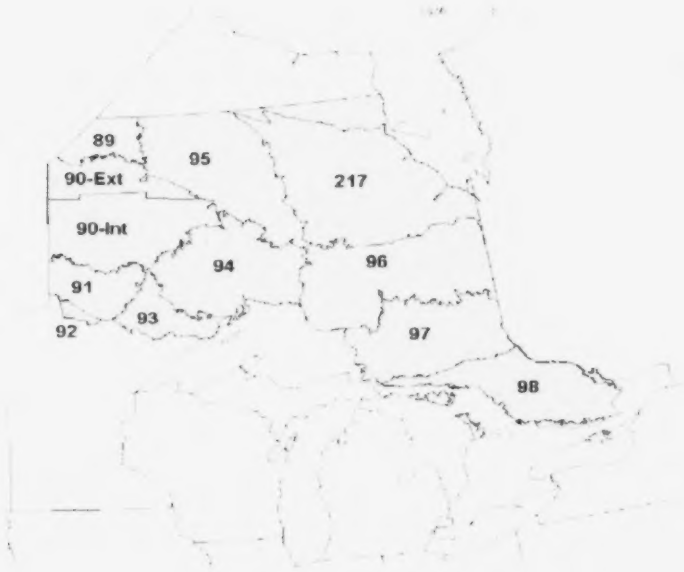


Figure 2.
The Ontario fire management zone (shaded) and national ecoregion designations within the zone.

Gridded lightning (20 × 20 km cells), fire weather, and fuel data were used to develop a series of lightning fire occurrence data sets for the province. The fire ignition and arrival models estimate the mean probability of occurrence of a fire under given conditions. The probability of any individual strike causing an ignition is quite low (typically <0.01) even under dry conditions. The expected number of fires for any cell on any day can be calculated by multiplying the probability of ignition by the number of strikes. However, level of protection analysis systems like Ontario's LEOPARDS (see section 3.4) require input data describing individual fire occurrences and attributes associated with each fire. As such, simulation methods must be used to generate fire occurrence scenarios.

Ignition Date

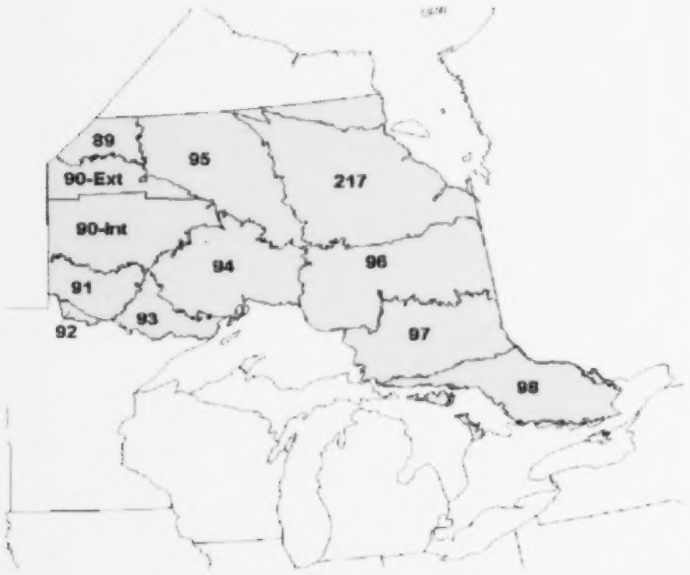
The ecoregion-specific ignition models were used to estimate the daily probability of a lightning strike causing an ignition in a specific cell on a specific day. The number of lightning strikes in each cell was used and the number of ignitions (or successes) was drawn randomly from a binomial distribution. The day of ignition was recorded as the fire start date.

Detection Date

For each fire ignited by a lightning strike, weather information for 21 days after the start date were used to evaluate the daily probability that the ignition on the forest floor would be detected (defined as 'fire arrival'). The 21-day window was based on an analysis of the OMNR fire record archive. Using the ecoregion-based probability models, each day a binary value, representing fire arrival, was drawn randomly from a binomial distribution from the start date until a success occurred (FIRE=1) or until 21 days had lapsed. By definition, each smouldering ignition modelled here represents a lightning fire ignition that eventually becomes a spreading and detected fire and is recorded by the fire management agency. As such, if there were no successes drawn randomly from the binomial model within the 21-day period, the day on which the probability of spread and detection was maximal was used as the detection date.

Location

The location of each ignition was determined by randomly drawing a latitude and longitude from uniform probability distributions. This seemed a reasonable approach given the variability in lightning strike position observed even for small well-defined storms.



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Location

The location of each ignition was determined by randomly drawing a latitude and longitude from uniform probability distributions. This seemed a reasonable approach given the variability in lightning strike position observed even for small well-defined storms.

People-caused Fire Occurrence Scenarios

Ecoregion specific people-caused fire occurrence models were developed for Ontario in a separate study (Wotton *et al.* 2003) and used with daily General Circulation Model scenarios to project potential increases in people-caused fire occurrence of about 18% by the period 2020-2040 and around 50% by 2100. The models were developed using Poisson regression (McCullagh and Nelder 1989) building on work originally done in Ontario (Martell *et al.* 1987,1989).

Weather from the centre of each ecoregion was used along with the Poisson people-caused fire occurrence models to create a mean expected number of people-caused fires for each day for fire seasons from 1992-2001. Years were selected to match the lightning fire ignition simulations developed, and as such, 1999 was not included in this analysis. A simulated set of daily people-caused fire occurrence numbers was created by drawing a series of random values from a Poisson distribution with daily mean values determined by the ecoregion-specific model and the FWI System codes.

Location

People-caused fires tend to be clustered around areas where there is both forest (or other receptive fuels) and land use by people. As such, the locations of previous people-caused fires in each ecoregion were used to determine the potential locations of fires in the simulated data set. That is, for each ecoregion a list of the previous 20 years of fire locations was assembled, and fires from the simulation data sets were randomly assigned (by drawing from a uniform random distribution) a location from this list.

Complete Fire Occurrence Scenarios

Combining people-caused and lightning-caused fire occurrence data sets created scenarios of fire occurrence for the province of Ontario for the nine-year period from 1992-2001 (excluding 1999). However the use of Ontario's Level of Protection Analysis System (LEOPARDS) requires information about each fire that is not available from the probability models created in this analysis; that is a fire report time, a fuel type in which the fire started spreading, a size at detection, and an estimated rate of spread at the time of detection. These attributes were assigned to each fire in the fire occurrence scenarios based on frequency distributions developed from historical fire data.

Report Time

Report time represents the time of day the fire was reported to the fire management agency. It was felt that the most reasonable approach for assigning a report time for each simulated fire occurrence was to draw on the records of previously recorded report times, as these presumably capture some information about the timing of detection flights and patterns of other, less organized detection methods. A frequency distribution of report times throughout the day was created in each ecoregion for lightning and people-caused fires separately using fire record data spanning the years 1976-2001. In ecoregions with a large sample of fires, the distribution was fairly normally distributed and centred on mid-afternoon. The differences between people- and lightning-caused fire report time distributions were slight in some cases and pronounced in others. Figures 3 and 4 exemplify these frequency distributions for ecoregion 90 (located in the Intensive Zone) in northwestern Ontario for lightning- and people-caused fires. A complete set of figures showing frequency distributions for each ecoregion and cause is presented in the Appendix. Using these frequency distributions, a report time was randomly chosen for each fire in the simulated data sets.

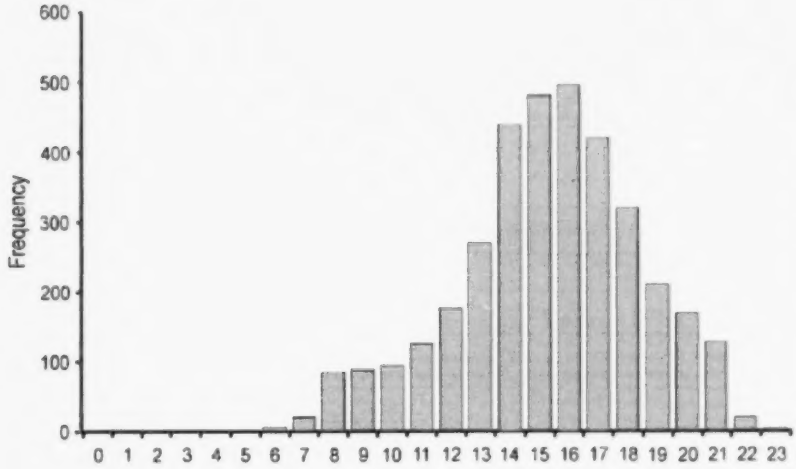

Figure 3.
Frequency distribution of lightning-caused fire report time for the Intensive Zone portion of ecoregion 90 based on fire archive data from 1976-2001.

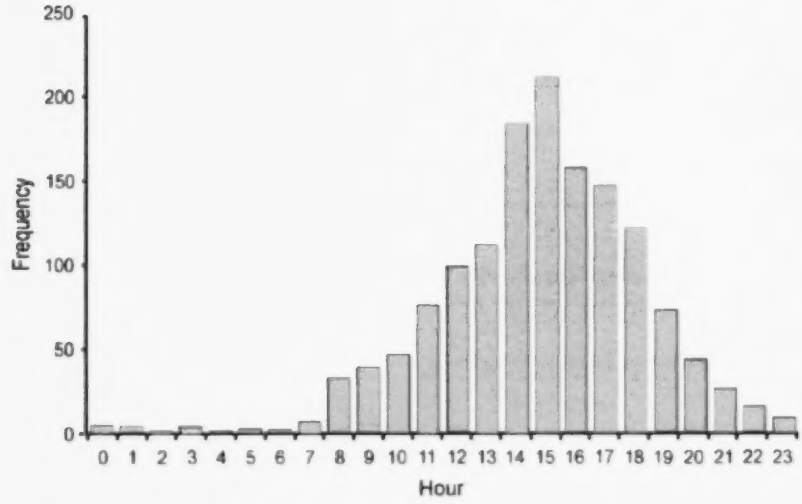

Figure 4.
Frequency distribution of people-caused fire report time for the Intensive Zone portion of ecoregion 90 based on fire archive data from 1976-2001.

Fuel Type

The LEOPARDS system requires an estimate of fuel type from one of 10 distinct fuel categories: grass, slash, shrubs, insect-killed conifer, conifer with vertical fuel continuity, conifer with a separated crown, mixedwood, deciduous, other, and a 'fueltype unknown' category[1]. As one might expect fires to ignite more readily in one fuel type over another (e.g., lightning fires ignite in a closed canopy conifer stand much more readily than in a mature, more open canopied deciduous stand), the fuel type record for historical fires was used to create a simple frequency distribution of fire occurrence in each of these fuel types in each ecoregion. Individual frequency distributions for lightning- and people-caused fires were built for each ecoregion. These frequency distributions (summarized in Tables 1 and 2) reveal strong differences between the fire occurrence frequency in fuel types for lightning- and people-caused fires. For instance, while virtually no lightning-caused fires occur in grass, this fuel type contains a substantial proportion of the people-caused fires across the province. Each simulated fire was randomly assigned a fuel type using the frequency distributions for each ecoregion and fire cause.

[1] These forest types within the LEOPARDS system are assigned to Canadian Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992) fuel types O1a(CUR=95%), S-1, D-1, M-3/M-4(PDF=90%), C-2, C-3, M-1(50%)/M-2(50%), D-1, S-1, and C-3, respectively

Table 1. Frequency (as a percentage) of lightning-caused fire occurrence in each of the 10 Ontario fuel type categories for each ecoregion using reported fuel types from the OMNR fire record archive for 1976-2001.

	Ontario Fuels Classification									
Ecoregion	Grass	Slash	Shrub	Insect killed conifer	Conifer vertical	Conifer separate	Mixed-wood	Hard-wood	Other	No data
89	0.0	0.4	2.7	0.4	32.0	25	1.6	0.4	1.2	36
90 (INT)	0.8	4.9	3.9	1.7	26.4	32.2	8.8	0.7	16.9	3.6
90 (EXT)	0.6	0	1.5	0.4	28.8	24.7	3.0	0.0	6.2	34.8
91	3.7	6.0	13.5	1.5	16.1	28.4	17.9	1.8	9.7	1.3
93	1.9	8.1	8.4	3.0	14.8	25.3	27.2	0.9	7.9	2.4
94	1.5	11.8	7.4	3.2	24.4	20.7	17.0	1.4	10.2	2.3
95	0.6	0.6	3.1	0	46.3	20.5	7.4	0.2	3.4	17.7
96	3.4	15.4	11.5	3.3	15.6	15.2	26.0	3.3	5.6	0.7
97	1.5	6.1	11.0	2.6	13.2	18.3	36.6	3.4	6.3	1.0
98	6.9	3.1	17.6	0.4	7.0	22.8	29.6	7.7	4.3	0.3
217	6.5	1.2	3.8	0.0	36.8	27.0	5.3	0.0	3.6	15.8

Table 2. Frequency (as a percentage) of people-caused fire occurrence in each of the 10 Ontario fuel type categories for each ecoregion using reported fuel types from the OMNR fire record archive for 1976-2001.

	Ontario Fuels Classification									
Ecoregion	Grass	Slash	Shrub	Insect killed conifer	Conifer vertical	Conifer separate	Mixed-wood	Hard-wood	Other	No data
89	27.3	1.3	2.6	0.0	11.7	23.4	16.9	1.3	9.1	6.5
90 (INT)	19.6	11.8	8.2	1.3	14.0	17.2	11.3	0.3	13.2	2.8
90 (EXT)	0.0	0.0	0.0	0.0	19.0	19.0	4.8	0.0	23.8	33.3
91	33.6	5.6	15.7	0.8	6.5	14.1	12.7	0.9	9.0	1.0
93	42.1	5.9	7.7	0.7	6.9	12.3	10.6	0.5	11.6	1.6
94	34.0	17.8	8.2	1.3	7.8	8.7	8.7	1.2	11.2	1.1
95	13.0	10.6	6.0	0.7	27.9	19.3	9.3	0.3	7.3	5.6
96	43.5	14.3	9.7	0.6	4.5	5.6	10.0	0.7	10.4	0.7
97	27.0	10.3	14.7	1.0	5.7	9.8	17.2	2.4	10.6	1.4
98	41.0	2.3	21.0	0.2	3.4	10.8	11.1	2.7	6.8	0.8
217	12.8	7.8	13.3	0.0	18.3	18.3	10.6	1.4	10.1	7.3

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Ecoregion	Grass	Slash	Shrub	Insect killed conifer	Conifer vertical	Conifer separate	Mixed-wood	Hard-wood	Other	No data
89	0.0	0.4	2.7	0.4	32.0	25	1.6	0.4	1.2	36
90 (INT)	0.8	4.9	3.9	1.7	26.4	32.2	8.8	0.7	16.9	3.6
90 (EXT)	0.6	0	1.5	0.4	28.8	24.7	3.0	0.0	6.2	34.8
91	3.7	6.0	13.5	1.5	16.1	28.4	17.9	1.8	9.7	1.3
93	1.9	8.1	8.4	3.0	14.8	25.3	27.2	0.9	7.9	2.4
94	1.5	11.8	7.4	3.2	24.4	20.7	17.0	1.4	10.2	2.3
95	0.6	0.6	3.1	0	46.3	20.5	7.4	0.2	3.4	17.7
96	3.4	15.4	11.5	3.3	15.6	15.2	26.0	3.3	5.6	0.7
97	1.5	6.1	11.0	2.6	13.2	18.3	36.6	3.4	6.3	1.0
98	6.9	3.1	17.6	0.4	7.0	22.8	29.6	7.7	4.3	0.3
217	6.5	1.2	3.8	0.0	36.8	27.0	5.3	0.0	3.6	15.8

Table 2. Frequency (as a percentage) of people-caused fire occurrence in each of the 10 Ontario fuel type categories for each ecoregion using reported fuel types from the OMNR fire record archive for 1976-2001.

	Ontario Fuels Classification									
Ecoregion	Grass	Slash	Shrub	Insect killed conifer	Conifer vertical	Conifer separate	Mixed-wood	Hard-wood	Other	No data
89	27.3	1.3	2.6	0.0	11.7	23.4	16.9	1.3	9.1	6.5
90 (INT)	19.6	11.8	8.2	1.3	14.0	17.2	11.3	0.3	13.2	2.8
90 (EXT)	0.0	0.0	0.0	0.0	19.0	19.0	4.8	0.0	23.8	33.3
91	33.6	5.6	15.7	0.8	6.5	14.1	12.7	0.9	9.0	1.0
93	42.1	5.9	7.7	0.7	6.9	12.3	10.6	0.5	11.6	1.6
94	34.0	17.8	8.2	1.3	7.8	8.7	8.7	1.2	11.2	1.1
95	13.0	10.6	6.0	0.7	27.9	19.3	9.3	0.3	7.3	5.6
96	43.5	14.3	9.7	0.6	4.5	5.6	10.0	0.7	10.4	0.7
97	27.0	10.3	14.7	1.0	5.7	9.8	17.2	2.4	10.6	1.4
98	41.0	2.3	21.0	0.2	3.4	10.8	11.1	2.7	6.8	0.8
217	12.8	7.8	13.3	0.0	18.3	18.3	10.6	1.4	10.1	7.3

Detection Size

Fire size at detection was selected randomly from frequency distributions built from the analysis of historical fire size information from the years 1976-2001. Individual distributions for lightning- and people-caused fires were constructed for each ecoregion. Fire sizes at report time were randomly drawn from these distributions for each simulated fire in an ecoregion. Summaries of these distributions are described in Table 3 for lightning-caused fires and in Table 4 for people-caused fires. The size of a fire at detection should depend on fire spread conditions between start date and detection date, and a detailed attempt to model this value involves examining fire weather, fuel moisture, and potential fire growth in the affected fuel type. Since most fires detected in Ontario were recorded as 0.1 ha and the fuel type was randomly selected, the random choice of detection size from observed values without regard for weather conditions seemed reasonable.

Initial Rate of Spread

The LEOPARDS system requires an estimate of the rate of spread of a fire. The Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) was used in conjunction with the Initial Spread Index (ISI), the Build-up Index (BUI) (calculated on the detection date of the fire using the FWI System), and the fuel type associated with the fire to estimate an initial rate of spread for each fire.

Table 3. Percentages of lightning-caused fires detected in various size fire classes at detection for each ecoregion in Ontario based on fire report archives for 1976-2001.

Fire size (ha)	Ecoregion										
	89	90 (INT)	90 (EXT)	91	93	94	95	96	97	98	217
≤ 0.1	15.3	63.4	26.9	74.9	69.2	62.4	23.6	56.0	69.0	58.3	17.3
≤ 1.0	34.6	92.3	57.8	96.7	96.4	91.1	50.4	88.8	96.0	92.9	37.2
≤ 10.0	59.0	98.5	80.6	99.9	99.8	98.7	74.0	98.6	99.8	99.8	61.9
≤ 100.0	79.1	99.6	94.7	100	100	99.8	89.3	100	100	100	83.0
> 100	20.8	0.4	5.3	0.0	0.0	0.2	10.7	0.0	0.0	0.0	17.0

Table 4. Percentages of people-caused fires detected in various fire size classes for each ecoregion in Ontario based on fire report archives for 1976-2001.

Fire size (ha)	Ecoregion										
	89	90 (INT)	90 (EXT)	91	93	94	95	96	97	98	217
≤ 0.1	63.6	65.8	38.1	60.7	64.3	67.5	57.1	54.6	60.8	65.3	44.3
≤ 1.0	90.9	92.8	76.2	90.0	92.1	93.3	83.4	84.7	89.7	97.8	73.0
≤ 10.0	97.4	98.7	81.0	97.9	99.1	99.4	95.7	97.7	98.6	99.3	90.0
≤ 100.0	100	99.8	90.5	99.8	99.9	100	98.7	99.8	100	100	96.8
> 100	0	0.2	9.5	0.2	0.1	0	1.3	0.2	0	0	3.2

Detection Size

Fire size at detection was selected randomly from frequency distributions built from the analysis of historical fire size information from the years 1976-2001. Individual distributions for lightning- and people-caused fires were constructed for each ecoregion. Fire sizes at report time were randomly drawn from these distributions for each simulated fire in an ecoregion. Summaries of these distributions are described in Table 3 for lightning-caused fires and in Table 4 for people-caused fires. The size of a fire at detection should depend on fire spread conditions between start date and detection date, and a detailed attempt to model this value involves examining fire weather, fuel moisture, and potential fire growth in the affected fuel type. Since most fires detected in Ontario were recorded as 0.1 ha and the fuel type was randomly selected, the random choice of detection size from observed values without regard for weather conditions seemed reasonable.

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≤ 0.1	15.3	63.4	26.9	74.9	69.2	62.4	23.6	56.0	69.0	58.3	17.3
≤ 1.0	34.6	92.3	57.8	96.7	96.4	91.1	50.4	88.8	96.0	92.9	37.2
≤ 10.0	59.0	98.5	80.6	99.9	99.8	98.7	74.0	98.6	99.8	99.8	61.9
≤ 100.0	79.1	99.6	94.7	100	100	99.8	89.3	100	100	100	83.0
> 100	20.8	0.4	5.3	0.0	0.0	0.2	10.7	0.0	0.0	0.0	17.0

Table 4. Percentages of people-caused fires detected in various fire size classes for each ecoregion in Ontario based on fire report archives for 1976-2001.

Fire size (ha)	Ecoregion										
	89	90 (INT)	90 (EXT)	91	93	94	95	96	97	98	217
≤ 0.1	63.6	65.8	38.1	60.7	64.3	67.5	57.1	54.6	60.8	65.3	44.3
≤ 1.0	90.9	92.8	76.2	90.0	92.1	93.3	83.4	84.7	89.7	97.8	73.0
≤ 10.0	97.4	98.7	81.0	97.9	99.1	99.4	95.7	97.7	98.6	99.3	90.0
≤ 100.0	100	99.8	90.5	99.8	99.9	100	98.7	99.8	100	100	96.8
> 100	0	0.2	9.5	0.2	0.1	0	1.3	0.2	0	0	3.2

LEOPARDS Simulations

To investigate the effect of changing fuel moisture and fire occurrence patterns on the effectiveness of Ontario's fire management agency, fire weather and fire occurrence scenarios were used within the province's level of protection analysis system (LEOPARDS) (McAlpine and Hirsch 1999). LEOPARDS is a 'level of forest fire protection' analysis tool developed by the OMNR based on work by Martell *et al.* (1983, 1984, 1995) and others. It is a complex model that simulates fire suppression activity (primarily initial attack) on fires occurring within the province's fire management area. The system uses fire occurrence, fire weather, and fire danger data sets as well as provincial policy, infrastructure (e.g., location of attack bases), and suppression resource information. The program simulates daily resource deployments and initial attack activities throughout the province over multi-year simulation periods and provides information on resource use, the number of fires that escape initial attack, area burned, and summaries of the cost of fire management operations.

Initially, the study of effects of climate change on Ontario's fire management organization was carried out using observed fire occurrence from the 1990s and future fire weather and fuel moisture scenarios for each decade. Accordingly, the only effects resulted from drier fuel conditions, which caused a higher percentage of fires to escape initial attack. Using this methodology, the percentage of increase in escaped fires and total management cost is illustrated in Figure 5. However, this original methodology did not account for potential increases in fire occurrence. Such increases would not necessarily result in similar (linear) increases in the numbers of escaped fires or operating costs as extra fires in the suppression system have the potential to overload available suppression resources, leading to much higher probabilities of fires escaping initial attack.

Current and future fire weather, fire danger, and fire occurrence scenarios were analyzed with LEOPARDS using Ontario's current fire suppression rules and resource levels. As fire occurrence on any particular day under given conditions has a random element, a number of simulations were completed for each weather scenario. Five simulations from each of the current (or baseline), 2040 (approximately $2xCO_2$), and 2090 (approximately $3xCO_2$) scenarios were analysed with LEOPARDS. Due to computational time limitations, simulations were not completed for each future decade.

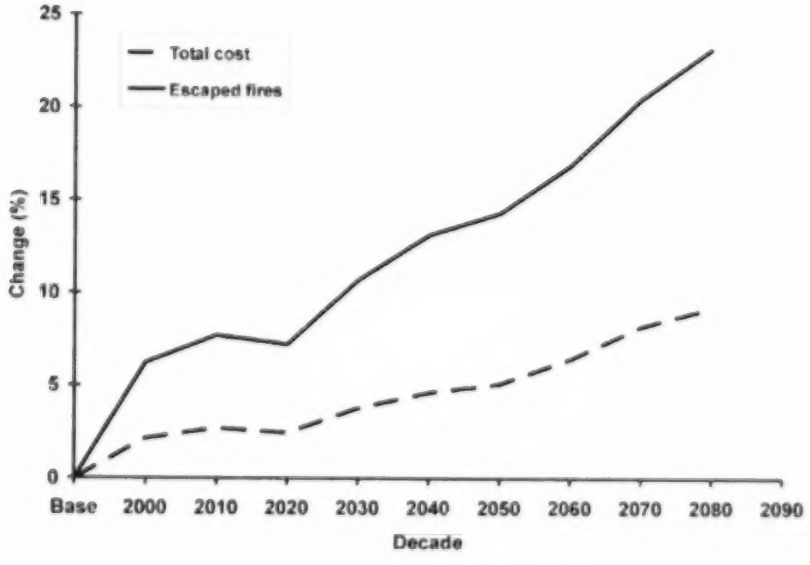

Figure 5.
Projected percent change in total cost and number of escaped fires for the decades 2000-2090 relative to 1990 (base) fire occurrence in Ontario.

Results and Discussion

Future Fire Climate

Analysis focused mainly on the decades of 2040 and 2090 as these represent the approximate times of doubling and tripling (over 1990 levels) of CO_2 in the atmosphere under current scenarios of greenhouse gas emissions. Figure 6 shows the mean summertime (May through August) temperature anomalies for the future decades of the 2040s and the 2090s subtracted from the baseline period of 2000. The model identifies a potential temperature increase of 1.0 to 1.5 °C by 2040 and 4.0 to 5.0 °C by 2090 across Ontario.

Total summertime rainfall ratios ($Rain_{2040}/Rain_{2000}$ and $Rain_{2090}/Rain_{2000}$) are depicted in Figure 7. These numbers represent the ratio of the total summertime rainfall in the future decade to total summertime rainfall in the baseline decade. In the 2040 scenario, changes in the total amount of rainfall over the summer months are very small across the entire province, not varying more than about 5% from current totals. In the 2090 scenario however, there is a tendency towards slightly wetter conditions with summertime rainfall increasing by 5 to 15% over baseline levels. To examine how projected changes in temperature and precipitation were broken down over the fire season, temperature and precipitation anomalies for two GCM grid cells covering northwestern and northeastern parts of Ontario were summarized (Table 5) for the decades of 2040 and 2090.

Fine fuel moisture content (FFMC) and duff moisture content (DMC) are important predictors of people- and lightning-caused fire occurrence. Both temperature and rainfall affect the moisture content of these fuel layers. Increasing temperature from climate change has the potential to create a drier forest at the surface and in the organic layers of the forest floor through increased evaporation (Boer *et al.* 2000). This moisture deficit may be offset by changes in the frequency and magnitude of precipitation in some regions (Flannigan *et al.* 1998) or enhanced by reductions in precipitation in other regions. Indeed, Stocks *et al.* (1998) and Flannigan *et al.* (1998, 2000) found that changes in climate projected by GCMs lead to increases in fire severity across much of Canada. Wotton *et al.* (2003) also found increases (indicating drier conditions) in mean values of fuel moisture indices across Ontario when using daily fire weather scenarios generated from GCM outputs. For the 2000, 2040, and 2090 fire weather scenarios, 90th percentile values of FFMC and DMC are shown in Figures 8 and 9, respectively. The 90th percentile values were chosen because fires occur and spread when fuel dries out, not necessarily under average fuel moisture conditions. Both these indices of fuel moisture show shifts to drier conditions by the end of the 21st Century, which implies a change to conditions more favourable for the ignition and spread of wildfires.

Table 5. Mean monthly temperature differences (ΔT) and precipitation ratios ($P_{FUTURE}/P_{PRESENT}$) for 2040 and 2090 using the year 2000 (1995 to 2004) as a baseline

Month	Northwestern Ontario 50.1°N by 93.75°W				Northeastern Ontario 50.1°N by 82.5°W			
	2040		2090		2040		2090	
	ΔT (°C)	P_{2040}/P_{2000}	ΔT (°C)	P_{2090}/P_{2000}	ΔT (°C)	P_{2040}/P_{2000}	ΔT (°C)	P_{2090}/P_{2000}
April	3.0	1.19	6.5	1.6	1.1	0.91	5.3	1.18
May	2.1	1.08	6.2	1.05	2.2	1.13	7.2	1.18
June	2.9	0.79	6.5	0.87	2.6	0.82	6.3	1.01
July	2.5	1	4.4	0.83	2.0	1.06	4.1	1.09
August	2.4	0.94	4.3	0.8	1.7	1.03	3.7	0.9
September	1.8	0.93	4.2	1.07	1.7	0.96	4.1	1.05

Results and Discussion

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	2040		2090		2040		2090	
	ΔT (°C)	P_{2040}/P_{2000}	ΔT (°C)	P_{2090}/P_{2000}	ΔT (°C)	P_{2040}/P_{2000}	ΔT (°C)	P_{2090}/P_{2000}
April	3.0	1.19	6.5	1.6	1.1	0.91	5.3	1.18
May	2.1	1.08	6.2	1.05	2.2	1.13	7.2	1.18
June	2.9	0.79	6.5	0.87	2.6	0.82	6.3	1.01
July	2.5	1	4.4	0.83	2.0	1.06	4.1	1.09
August	2.4	0.94	4.3	0.8	1.7	1.03	3.7	0.9
September	1.8	0.93	4.2	1.07	1.7	0.96	4.1	1.05

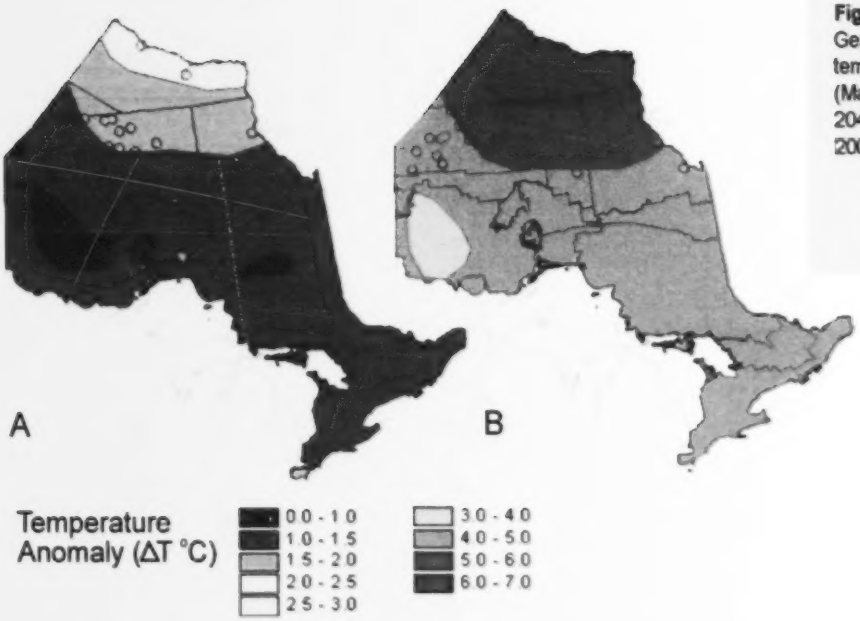

Figure 6.
General Circulation Model temperature difference (May-August) from (A) 2040-2000 and (B) 2090-2000.

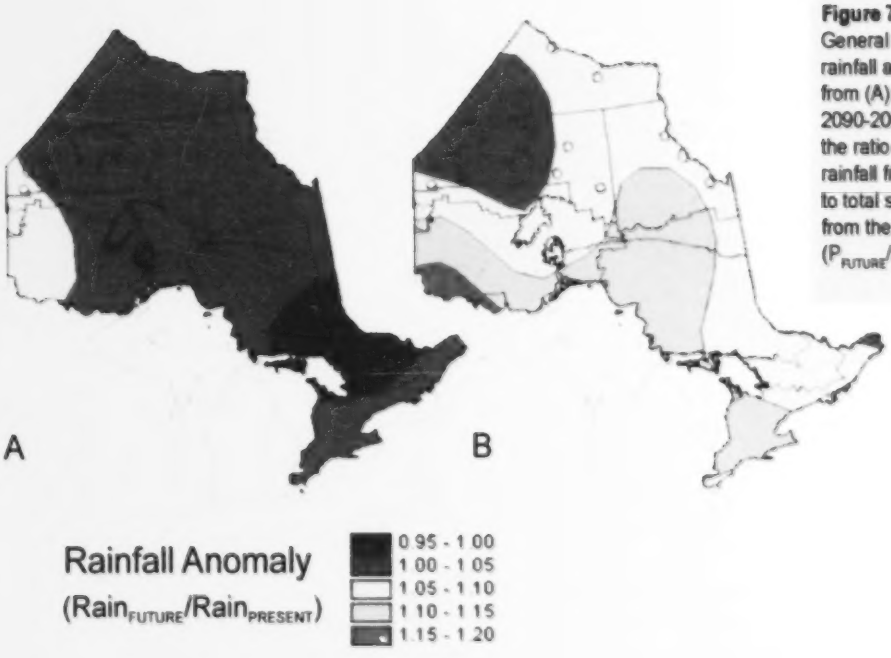

Figure 7.
General Circulation Model rainfall anomaly (May-August) from (A) 2040-2000 and (B) 2090-2000. Numbers represent the ratio of total summertime rainfall from the future period to total summertime rainfall from the baseline period ($P_{FUTURE}/P_{PRESENT}$).

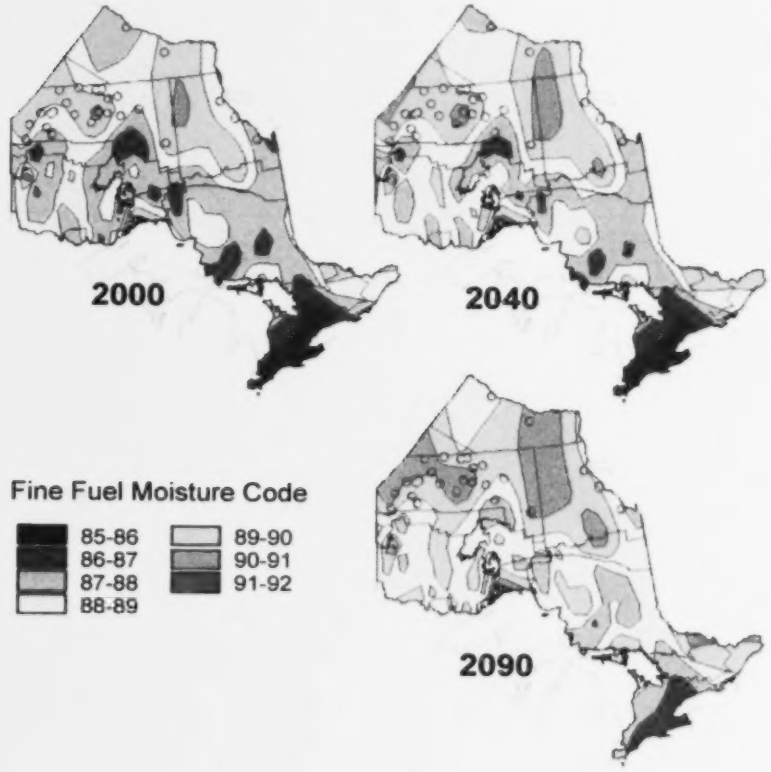

Figure 8.
July 90th percentile values of Fine Fuel Moisture Code for the years 2000, 2040, and 2090.

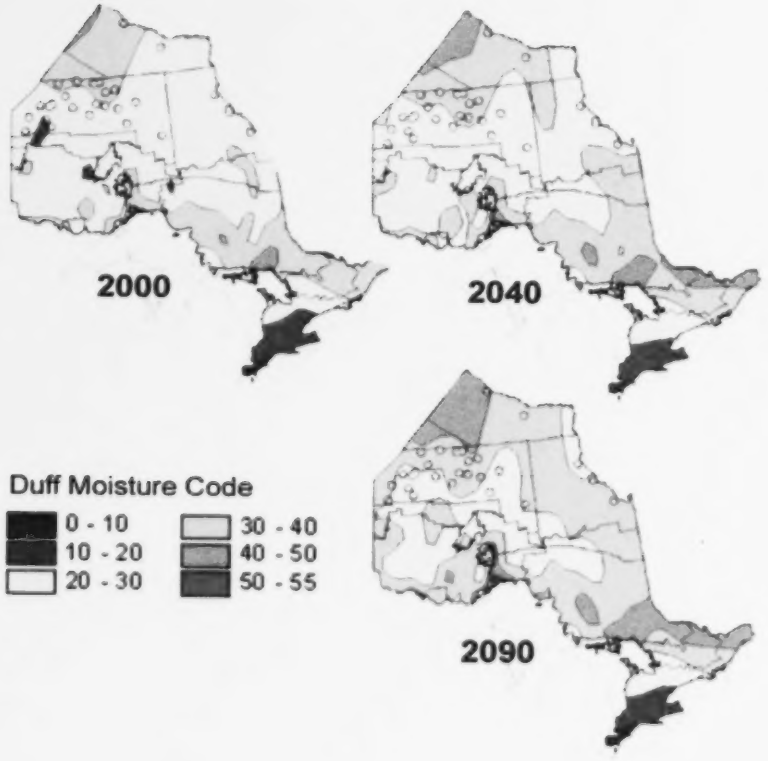

Figure 9.
July 90th percentile values of Duff Moisture Code for the years 2000, 2040, and 2090.

Future Fire Occurrence

To examine the coarse spatial distribution of the simulated fire locations, a map of lightning fire occurrence over the study period (1992-2001) for one simulation is shown in Figure 10, while the observed distribution of lightning fires for the same period is described in Figure 11. Similarly a map of people-caused fire occurrence over the study period for one simulation is shown in Figure 12, while actual fire occurrence is shown in Figure 13.

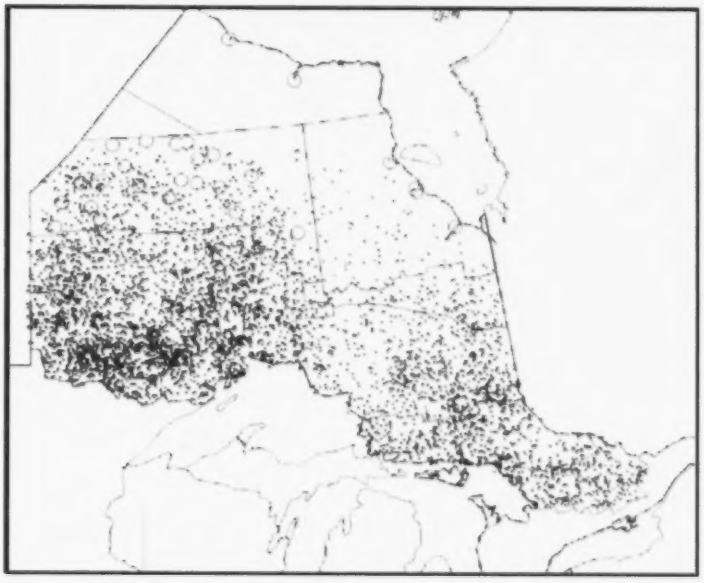

Figure 10.
Distribution of lightning fires from 1992-2001 (excluding 1999) from one simulation using the lightning fire occurrence probability models.

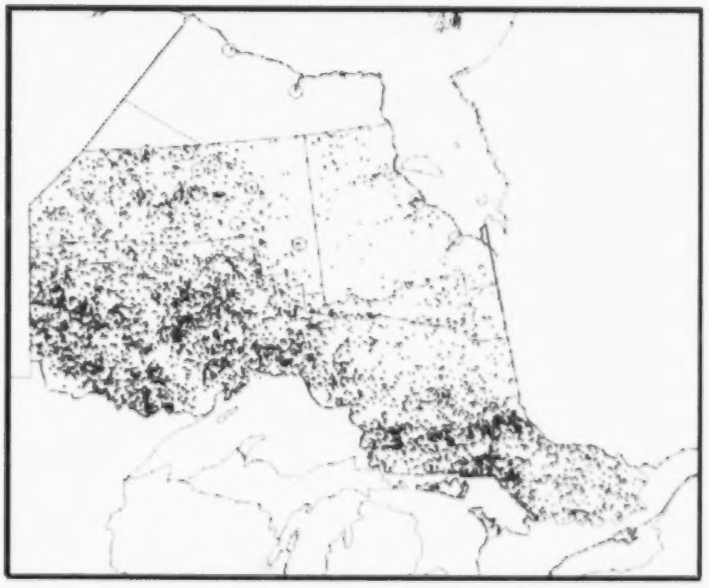

Figure 11.
Actual distribution of lightning fires in Ontario from 1992-2001 (excluding 1999).

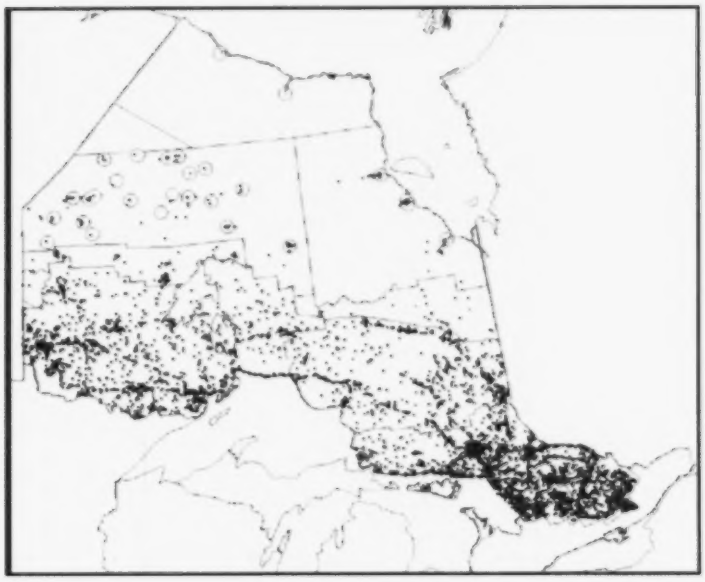

Figure 12.
Distribution of people-caused fires from 1992-2001 (excluding 1999) from one simulation using the Poisson prediction models.

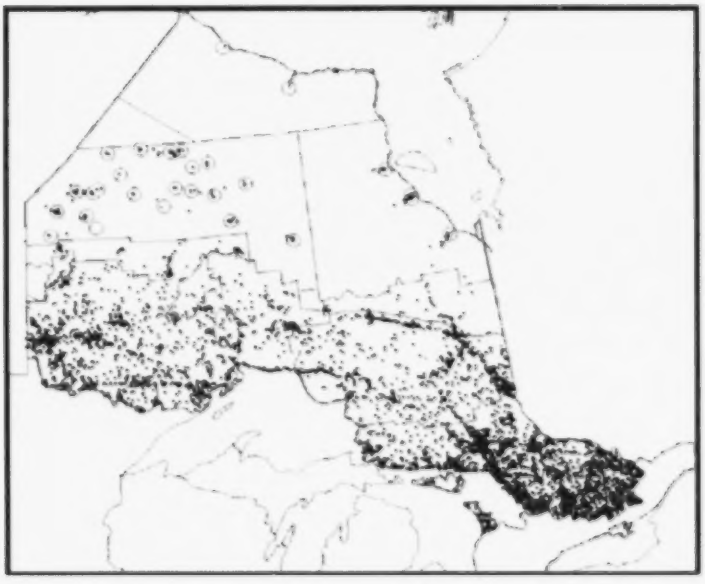

Figure 13.
Actual distribution of people-caused fires in Ontario from 1992-2001 (excluding 1999).

A number of lightning fire occurrence scenarios were simulated using each decade of future fire weather. Mean annual numbers of fires in each ecoregion are summarized for the decades 2020, 2040, 2070 and 2090 in Table 6. These results show increasing numbers of lightning-caused fires in future climates. Across the ecoregions, these increases range from 6 to 40% for the 2040 period and 30 to 40% for the 2090 period. Overall lightning-caused fire occurrence is predicted to increase by 24% by 2040 and 80% by 2090 across the area under forest fire management in Ontario. The simulations indicate that increased drying of the fuels from increased temperatures is not being offset by changes in precipitation over the fire season. Accordingly, drier fuels increase the probability that a lightning strike will cause an ignition.

Because current lightning strike occurrence data are being used in these predictions, differences in lightning strike frequency caused by changes in the intensity of convective activity are not included. The changes in fire activity predicted here are due strictly to changes in the moisture content of the fuels on the forest floor. Price and Rind (1993) predicted a 36% increase in cloud-to-ground lightning activity over land for the mid-latitudes in the northern hemisphere for a $2xCO_2$ scenario (roughly 2050 in the CCC GCM) using the GISS GCM. This increase in lightning activity would increase the number of fire ignitions in Ontario beyond the increases indicated in the current study.

People-caused fire scenarios generated using the future fire climates and mean annual occurrence numbers are summarized for each set of decades in Table 7. Across the ecoregions, people-caused fires are projected to increase 4 to 14% by the 2040 and 19 to 90% by 2090. Overall, the number of people-caused fires in the province is expected to increase by 7% by the 2040s and by 26% by the 2090s. This projected increase in the number of fires is lower by about half those reported in Wotton *et al.* (2003). This lower frequency is likely due to the different

Table 6. Mean number of lightning-caused fires per year in each Ontario ecoregion for current and future fire weather and fuel moisture scenarios.

	Annual Number of Lightning-caused Fires					
		Calculated Decadal Fire Weather Scenario				
Ecoregion	Observed 1992-2001	2000	2020	2040	2070	2090
89	11.1	8.1	8.4	9.2	12.1	14.2
90-Int	103.7	79.9	80.7	102.7	135.8	148.7
90-Ext	12.7	9.1	8.6	9.7	10.5	12.9
91	56.9	59.3	61.5	73.3	110.1	114.9
93	44.1	45.4	48.8	59.8	84.8	87.1
94	112.2	114.9	136.2	161.9	268.2	270.7
95	54.3	41.9	45.2	53.8	70.8	79.3
96	57.1	46.5	47.3	49.4	63.7	64.9
97	96.7	33.8	84.8	93.7	107.1	117.7
98	76.3	63.6	63.4	75.3	85.1	91.8
217	3.7	10.4	10.6	11.1	13.4	13.8

Table 7. Mean number of people-caused fires per year in each Ontario ecoregion for current and future fire weather and fuel moisture scenarios.

	Mean Annual Number of People-caused Fires					
		Calculated Decadal Fire Weather Scenario				
Ecoregion	Observed 1992-2001	2000	2020	2040	2070	2090
89	4.4	3.3	3.3	3.5	4.0	4.3
90-Int	54.4	46.2	46.9	48.8	58.4	59.3
90-Ext	0.2	0.6	0.6	0.7	1.0	1.2
91	71.6	66.3	66.1	69.7	79.8	81.2
93	34.4	46.7	47.5	49.6	57.3	57.9
94	56.8	56.4	58.2	60.0	69.8	70.8
95	16.8	11.0	11.3	12.6	15.5	16.8
96	75.4	58.5	58.6	60.6	67.2	69.6
97	83.7	81.4	81.9	87.3	95.7	100.8
98	272.4	329.7	334.5	358.2	390.3	420.3
217	7.6	9.1	9.3	9.9	12.9	13.4

methods used to generate daily fire danger scenarios. The anomaly approach (Stocks *et al.* 1998) used in this study to generate future fire danger scenarios can be a more conservative method of generating future fuel moisture and fire danger scenarios. Use of this method was necessary, however, because current lightning strike data were used to generate lightning fire scenarios. Daily GCM output can be used to account for potential changes in temperature, precipitation, relative humidity, and changes in the frequency and duration of drought events, which play an important role in determining forest fire activity (Flannigan and Harrington 1988). Using daily GCM data to estimate future fuel moisture and fire danger levels, Flannigan *et al.* (1998, 2000) predicted greater variability in projected increases in forest fire severity levels.

Lightning- and people-caused fire predictions were then combined (Figure 14) to evaluate the total increase in fire activity across the province (in relation to total fire occurrence predicted over the baseline 2000 period) for future decades. In the early part of the 21st Century, increases in total fire occurrence in Ontario's fire region are relatively small. In the latter half of the century, greater increases are projected, with the annual number of fires increasing 28 to 100% by the final decade of the century. Overall, the average increase in the number of fires is 15% by 2040 and 50% by 2090 across the province's fire management area. Increases in total fire activity are greater in the western part of the province (Figure 15).

Forest Fire Management

Mean annual cost, percentage of escaped fires, and area burned in the protection zone are summarized for each set of five fire occurrence scenarios (for years 2000, 2040 and 2090) in Table 8. Using the year 2000 as a baseline, the number of escaped fires in the year 2040 increases by about 30%, which translates into a 16% increase in suppression costs to the fire management agency. These costs are considerably higher than the estimates made by combining future fire climate scenarios with current fire occurrence scenarios (Figure 5), which indicate a 13% increase in escaped fires and a 5% increase in fire management system costs by the year 2040. By the end of the 21st Century, escaped fires are projected to rise by about 80% in conjunction with a 54% increase in the overall cost to the provincial fire management organization.

Estimated carbon (C) emissions from fires burning in Ontario's fire management zone are also shown in Table 8. These values represent direct emissions due to fuel consumption and have been calculated using the ecozone average $kg \cdot C \cdot m^{-2}$ values from Amiro *et al.* (2001) (i.e., 1.24 $kg \cdot C \cdot m^{-2}$ for the Boreal Shield West ecozone and 1.00 $kg \cdot C \cdot m^{-2}$ for the Boreal Shield East ecozone) multiplied by an estimate of the area burned in each of these ecozones (based on the relative number of fires occurring in each zone for each scenario). The change in carbon emissions is quite similar to the change in area burned and shows an increase in direct carbon emissions from fire of approximately 700 $Gg \cdot C \cdot year^{-1}$. This number is based only on fires in the Intensive and Measured Protection Zones, and does not include carbon release from unsuppressed fires burning in the Extensive Zone.

These estimates do not account for the impact of a changing fire management organization. The current complement of fire suppression resources in Ontario has been optimized (for lowest cost) to the current level of fire activity. Changes to fire management activity would require a commensurate change in suppression resources in the province. While this would reduce the percent escape and total cost figures, these are still expected to rise substantially over current levels.

Table 8. Percentage of escaped fires, mean annual cost, area burned, and carbon emissions in the protection zone. Each number is the mean of five separate fire occurrence scenario runs. The number in parentheses is standard error of the mean.

	Scenario		
	2000	2040	2090
Escaped fires (%)	10.4 (0.1)	13.7 (0.2)	18.7 (0.1)
Fire management cost ($)	59,160,000 (310,000)	68,640,000 (480,000)	91,100,000 (240,000)
Area burned (in protection zone) ($ha \cdot year^{-1}$)	80,000	105,000	142,000
Carbon emissions ($Gg \cdot C \cdot year^{-1}$)	880	1,170	1,590

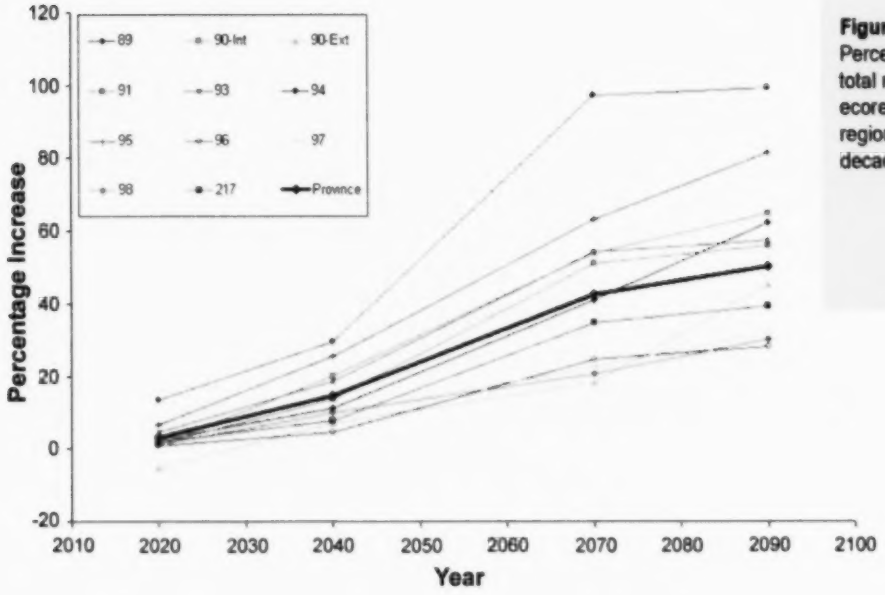

Figure 14.
Percentage increase in total number of fires in each ecoregion in Ontario's fire region for several future decades.

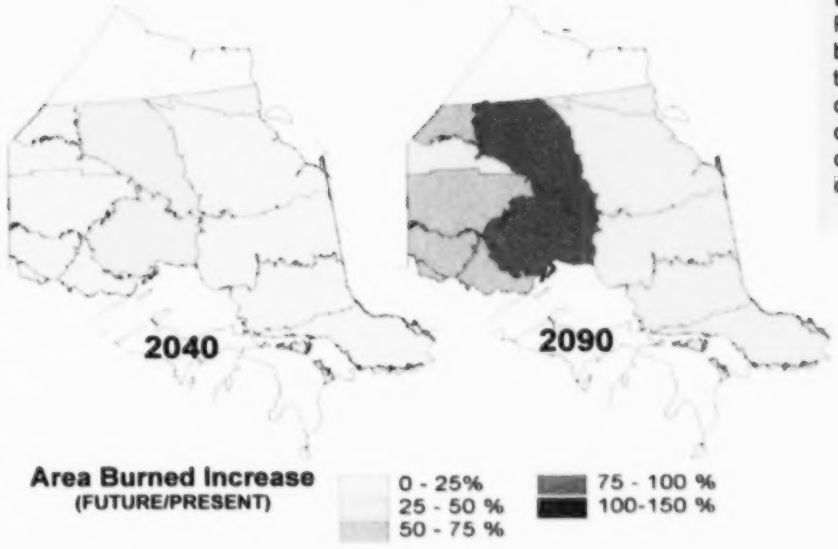

Figure 15.
Percentage increase (above baseline period 2000) in the total number of fires occurring in Ontario, based on ecoregion-specific models of lightning- and people-caused fire.

Summary

This investigation combines fire weather and fuel moisture scenarios derived from General Circulation Model (GCM) climate estimates with forest fire occurrence models and a level of protection analysis system (LEOPARDS) to estimate the impacts of climate change on the fire management system in Ontario. GCM climate scenarios show that the mean summertime temperature in Ontario will increase 1 to 1.5 °C by 2040 and 4 to 5 °C by 2090. This change in temperature will be accompanied by relatively small changes in regional precipitation. Changes in precipitation will not offset the potential moisture loss caused by increased evaporation from the forest floor, and therefore fuel moisture will decrease. This is predicted to lead to a 24% increase in the number of lightning-caused fires in the province by 2040 and an 80% increase by 2090. This estimated increase in lightning fire activity is conservative because it does not include any changes in current levels of lightning activity. Lightning strike activity is expected to increase in the future. The number of people-caused fires occurring in Ontario is expected to increase by at least 7% in 2040 and 26% in 2090, however these are conservative estimates because changing rainfall frequency patterns were not included in the models. Overall, the total amount of fire activity in Ontario's fire management area is expected to increase 15% by 2040 and 50% by 2100. The increased fire activity and fire behaviour potential caused by drier fuels will lead to a 30% increase in the number of fires that escape initial attack by the year 2040 and an 80% increase by the end of the 21st Century. The increased fire load is also expected to increase the cost of fire management in the province 16% by the year 2040 and 54% by 2090, exclusive of other inflationary pressures.

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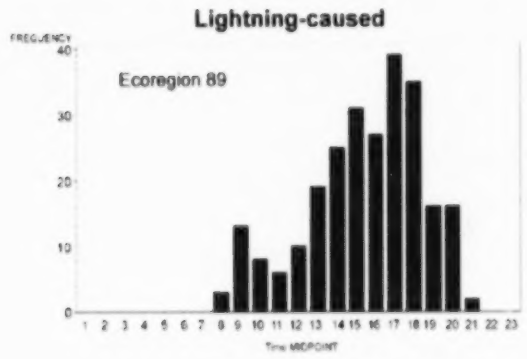
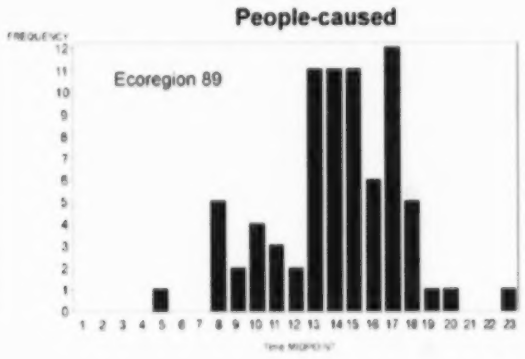
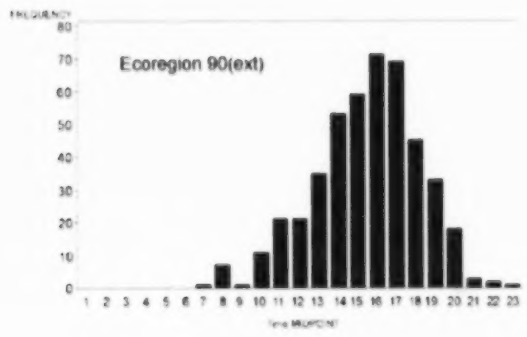
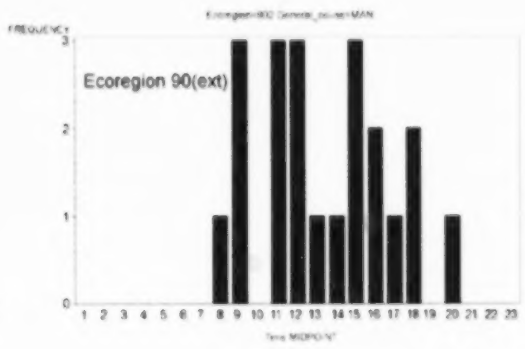
APPENDIX

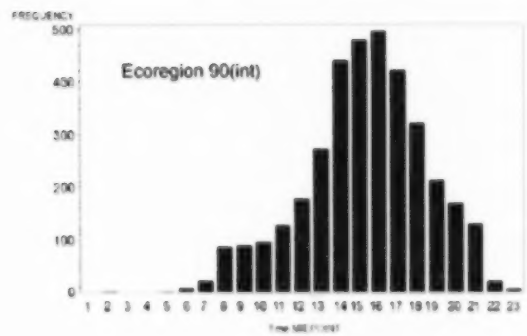
Frequency Distributions of Lightning- and People-caused Fire Detection Time for Each Ecoregion (see Figure 2 in text for map of ecoregions) in Ontario's Fire Management Region.

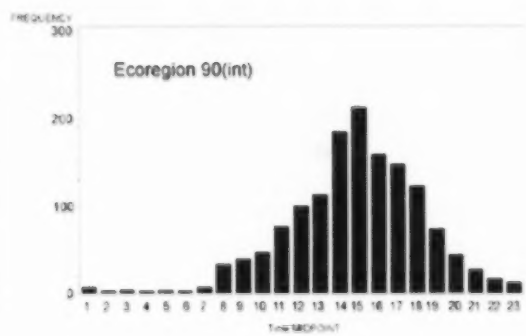


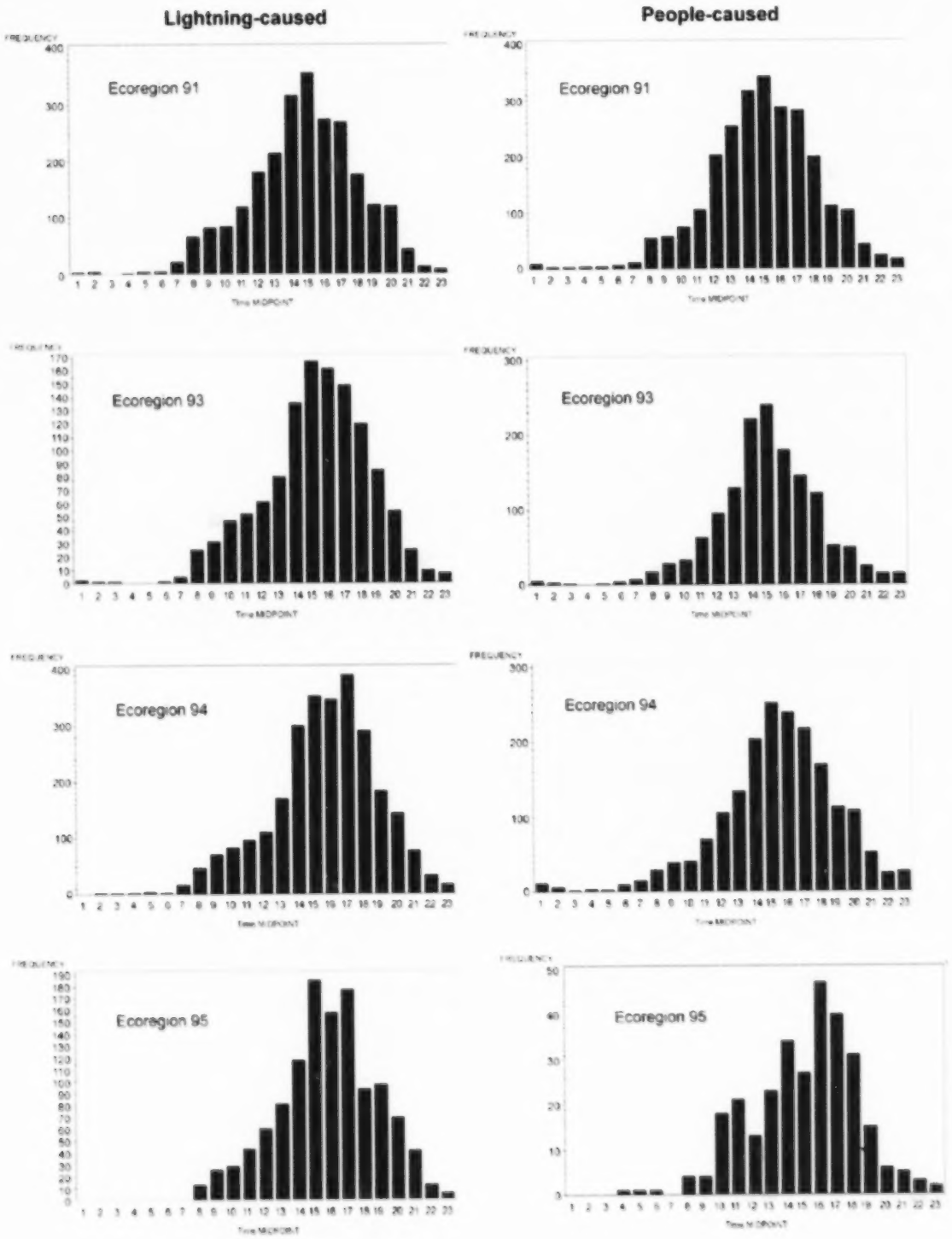








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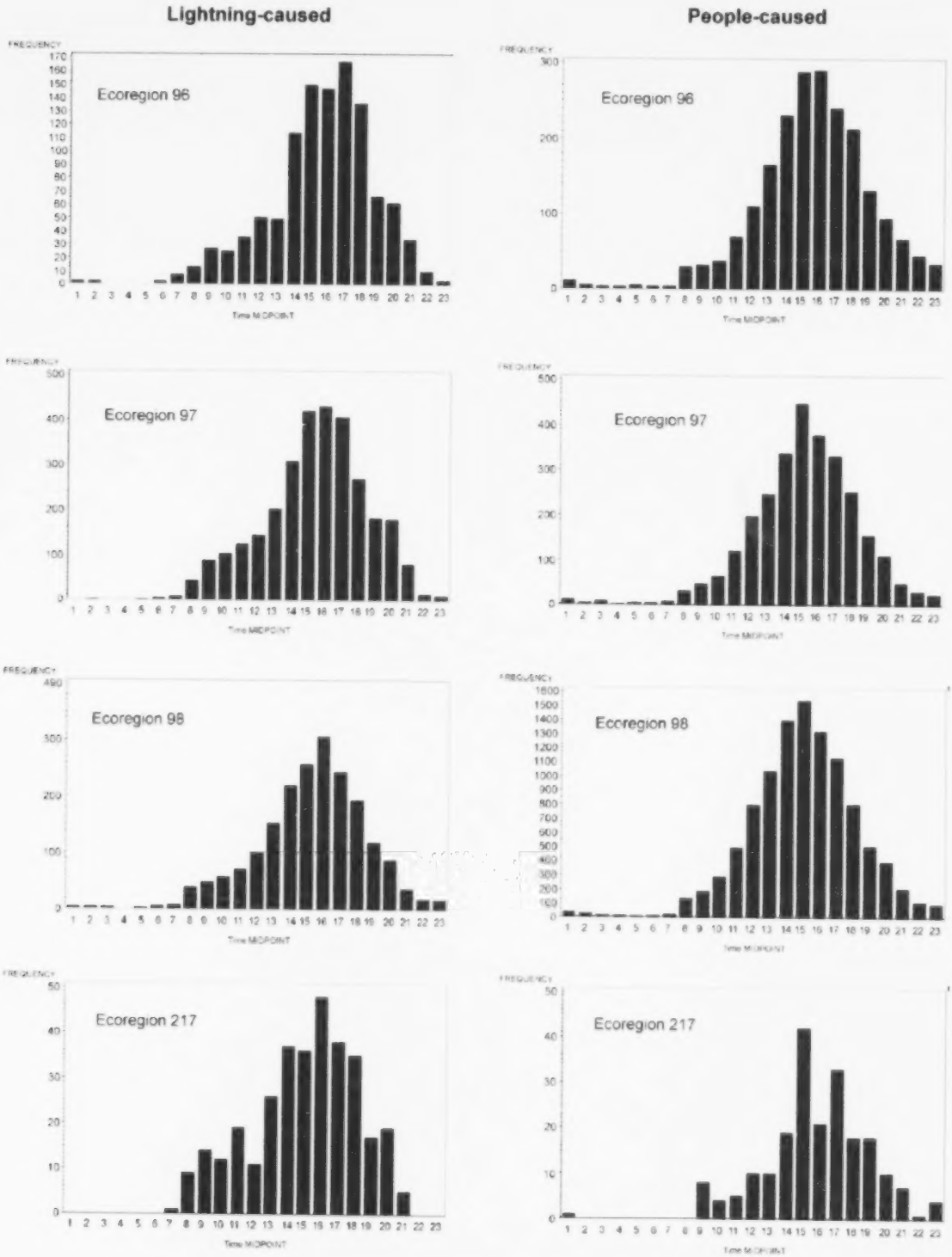
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